BOREAL ENVIRONMENT RESEARCH 21: 1–24
ISSN 1239-6095 (print) ISSN 1797-2469 (online)
Helsinki 8 April 2016

Operational correction of daily precipitation measurements in Finland

Antti Taskinen* and Kimmo Söderholm

*Finnish Environment Institute (SYKE), P.O. Box 140, FI-00251 Helsinki, Finland (*corresponding author's e-mail: antti.taskinen@ymparisto.fi)*

Received 19 Nov. 2014, final version received 8 Sep. 2015, accepted 8 Sep. 2015

Taskinen A. & Söderholm K. 2016: Operational correction of daily precipitation measurements in Finland. *Boreal Env. Res.* 21: 1–24.

An operational method for daily precipitation observation correction of aerodynamic, wetting and evaporation errors is presented. The aerodynamic correction method used has been developed for Finnish conditions when wind observations at the gauge are not available but the data from the nearest synoptic station can be used. Daily precipitation observations in Finland and its cross-boundary watersheds from the period 1961–2011 were corrected. It was discovered that the mean annual total sum of all gauges increased by 13.6% from 590.3 mm to 670.6 mm. The average overall proportions were 8.6%, 22.8% and 68.6% for evaporation, wetting and aerodynamic corrections, respectively. On a daily basis, the correction factor varied remarkably according to the form and intensity of precipitation, the median value being 1.21. Positive linear trends were identified in observed, corrected total and liquid precipitation, whereas a negative linear trend was obtained in corrected solid precipitation. The preliminary assessment using a watershed model indicated that the amount of correction is approximately correct for liquid precipitation but might slightly be too large for solid precipitation. Using corrected precipitation as a hydrological model input is recommended but a more comprehensive research is needed.

Introduction

The starting point of all hydrological considerations related to water balance studies is the knowledge of the amount and distribution of precipitation with respect to time and space. This information has almost solely been based on point measurements obtained from a can-type gauge elevated above the ground. To obtain better information for spatial variation of precipitation, gauges have been distributed over an area and bound into networks (Sevruk 1986b). In recent decades, remote sensing techniques have improved but gauge networks still play an important role as an independent source of precipitation information and also as a reference tool for weather radars (e.g. Collier 1986a, 1986b, Gjertsen and Dahl 2001, Saltikoff *et al*. 2015) and satellites (e.g. Bell and Kundu 2003).

Gauge precipitation measurements are always subject to various sources of errors. Sevruk (1986b) divided the sources as follows: (1) random and systematic errors of point precipitation measurements, (2) random error at the gauge site (due to local irregularities of topography and micro-climatic variations), and (3) random error of a gauge network (due to inadequate network density). Systematic error is believed to be the

Editor in charge of this article: Harri Koivusalo

most important source and it can be further divided into the following components: (1) aerodynamic, (2) wetting, (3) evaporation, (4) splash in and out, and (5) blowing and drifting snow. According to Førland *et al*. (1996), the most important of these for the Nordic countries is the aerodynamic error, but wetting and evaporation errors also have to be accounted for.

Korhonen (1944) and Dahlström (1970a, 1970b) were among the first to publish precipitation error considerations and correction studies for Nordic conditions to be followed later by e.g. Allerup and Madsen (1980), Tammelin (1984), Solantie (1986) and Dahlström *et al*. (1986). A pioneering and influential international workshop on the topic was held in 1985, resulting in a research report of a number of papers (Sevruk 1986a). In the same year, World Meteorological Organization (WMO) initiated a solid precipitation measurement intercomparison to evaluate national methods of measuring solid precipitation against methods with familiar accuracy and reliability, including past and current procedures, automatic systems and new methods of observation (Goodison *et al*. 1989). This brought about a number of investigations during the next twenty years or so. Some preliminary results were presented by Sevruk (1989a) and more profound, for instance, by Huovila *et al*. (1988) and Førland *et al*. (1996), who reported on the efforts of the Nordic countries to standardise precipitation correction methods and compare rain gauge types. Yang *et al*. (1995) showed comparisons between the Tretjakov and a double fence intercomparison reference (DFIR) in seven countries. Allerup *et al*. (1997) presented a statistical model for solid and mixed precipitation correction due to wind-induced errors. Yang *et al*. (1998) investigated the effects of environmental factors on the gauge catch and found that wind speed was the most important one. Moreover, Førland and Hanssen-Bauer (2000) evaluated results from the intercomparison project and parallel precipitation measurements of Tretjakov and Norwegian gauges and Yang and Ohata (2001) reviewed methods to determine bias correction terms of Tretjakov gauges and applied selected ones in Siberian regions for 1986–1992.

In the same continuum of studies, Bogdanova *et al*. (2002) presented the bias method for the standard Tretjakov gauge. The method accounts for the following corrections: (1) aerodynamic error, (2) joint effect of wetting, evaporation and condensation at the gauge collector interior, (3) trace precipitation, and (4) false precipitation (blowing snow flux into the gauge). Michelson (2004) implemented a statistical Dynamic Correction Model with the intent to perform a systematic correction of precipitation measurements from gauges found in and near the Baltic Sea's drainage basin. He found out that H&H-90 gauge underestimates precipitation by around 8% on average and its average correction factor is slightly smaller than that of the Tretjakov gauge's. Chvíla *et al*. (2005) showed that the wind-induced loss of liquid precipitation increases with increasing wind speed and decreasing intensity of precipitation. Sugiura *et al*. (2006) carried out an intercomparison of solid precipitation measurements to examine the catch characteristics of five different precipitation gauges, including Tretjakov. They found, for instance, that the daily catch ratios (observed precipitation/corrected precipitation) decreased more rapidly with increasing wind speed. Other investigations of challenges in measuring solid precipitation have been presented by e.g. Nitu and Wong (2010), Rasmussen *et al*. (2011) and Wolff *et al*. (2013). Sevruk *et al*. (2009) summarized the results of international precipitation measurement intercomparisons of WMO between 1955 and 2008.

The Finnish Environment Institute runs an automatic, operational hydrological watershed model called the Watershed Simulation and Forecasting System (WSFS). The system is described by Vehviläinen *et al*. (2005) and is available at http://www.environment.fi/waterforecast. WSFS is used for e.g. flood forecasting, real-time monitoring and climate change research. It covers the whole land-area of Finland in addition to the cross-boundary watersheds and its time step is one day. The water quality component VEMALA (Huttunen *et al*. 2016) simulates the transport of suspended solids, total phosphorus and total nitrogen. Main meteorological inputs are precipitation and temperature. This study was triggered by the need to improve the accuracy of the precipitation input and make the observations more spatially representative and temporally consistent by accounting for the main errors related to the gauge measurements, keeping in mind the operational nature — each observation is automatically corrected before usage — of the method application.

The main purpose of this article is to describe in a detailed fashion the method for correction of precipitation measurements consisting of the exposure method for aerodynamic correction in addition to wetting and evaporation corrections. The method was applied to every precipitation observation in Finland made between 1961 and 2011, using correction coefficients depending on gauge exposure information and type, both changing in time. Moreover, the aim was to check the data and the correction approach results for the purpose of operational hydrology by presenting the amount of increased precipitation at each gauge in different forms and at different time scales at each gauge keeping in mind the spatial aspects of Finnish weather conditions. Also the consistency of data was analysed for climate or other research utilizing long time series.

Climate and hydro-meteorological observations

Climate

Finland is located between 60° and 70° of northern latitude, a quarter of the country located north of the Arctic Circle. Finland lies between the Scandinavian mountains and the northern Russian plains. In the west and the south, it has a long coastline with numerous islands along the Baltic Sea (Finland's Fifth National Communication under the United Nations Framework Convention on Climate Change 2009). Due to its location, the climate of Finland has features of both marine and continental climates, depending on the direction of airflow. The mean temperature in Finland is many degrees higher than in most areas at the same latitudes. This is mostly due to airflows from the Atlantic warmed by the Gulf Stream but also because of the Baltic Sea and abundant inland waters. According to the Köppen-Geiger climate classification for Europe (Peel *et al*. 2007), Finland belongs to the class of cold climate without dry seasons and to the sub-class of cold summers with the exception of southern parts belonging to the sub-class of warm summers.

Observing hydro-meteorological variables

Precipitation

The meteorological data were mainly provided by the Finnish Meteorological Institute (FMI). Since cross-boundary watersheds were included in the study, data provided by Swedish Meteorological and Hydrological Institute, Norwegian Meteorological Institute and Hydrometeorological Centre of Russia were also used. In 1961–2011, there were three standard gauge types in Finland. Their descriptions are adapted from Huovila *et al*. (1988), Førland *et al*. (1996) and Goodison *et al*. (1998). The Wild precipitation gauge with a Nipher wind shield was used, with minor variations, as the standard gauge in 1908–1981. The cylindrical bucket of the Wild gauge is made of a 0.5-mm-thick brass sheet. The orifice area is 500 cm^2 and its height is 150 cm above the ground. Inside the bucket, there is a fixed conical partition with a drain hole, some 4 mm in diameter. The wind shield is a truncated cone made of galvanised steel.

In 1982, the Wild gauges were replaced by the Tretjakov gauges. Their cylindrical vessel is made of 0.5-mm-thick galvanised steel with a varnished, grey outer surface. The orifice is 200 cm^2 and it is placed at a height of 150 cm above the ground. Inside the bucket there is a cone-shaped partition with a large drainage hole. To reduce evaporation during summer, the drain hole is covered with a shield consisting of a funnel with a hole 7 mm in diameter. The spout of the vessel is about 215 mm from the bottom of the bucket. The bucket is placed inside a windshield made of 15 slats forming a cone, with the upper edges of the slats bent outwards at an angle of 70° to be horizontal. The slats are on a level with the rim of the bucket.

A new standard Finnish bucket, H&H-90, using the Tretjakov gauge wind shield, went into operation at all manual observation stations on 1

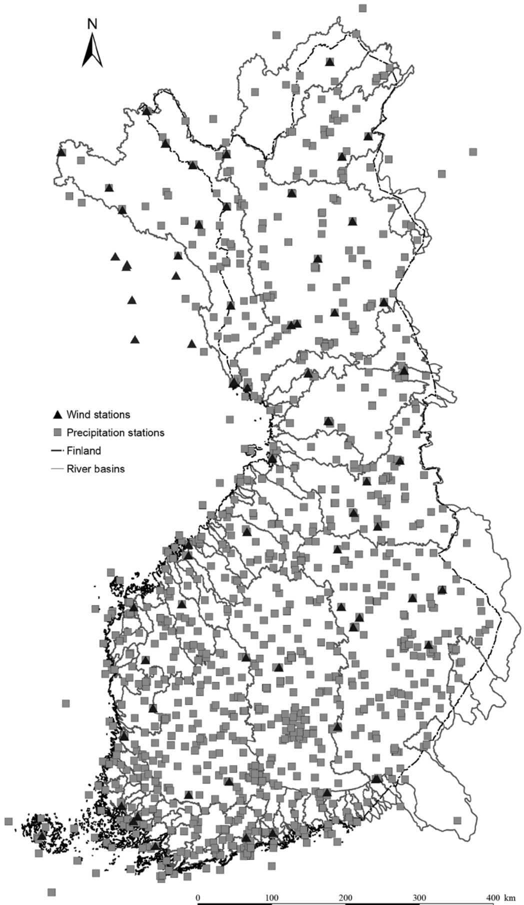

Fig. 1. Precipitation and regionally-representative wind stations in 1961–2011.

January 1992. It is made of aluminium and covered inside with white PTFE and is painted white on the outside. There is no spout in the bucket and the height of the bucket is the same as that of the Tretjakov bucket (40 cm).

In the latest years of the studied period, an instrument based on the weighing principle, Vaisala All Weather Precipitation Gauge VRG101 (Nitu and Wong 2010), was also used. It has a similar windshield to that of the Tretjakov gauge and hence the same aerodynamic correction method is assumed to be applicable to it too.

Since 1961, WSFS has used precipitation data from a total of 1051 gauges, of which 17, 6 and 9 are located in Sweden, Norway and Russia, respectively (Fig. 1). The descriptions of the gauges used Sweden and Norway can also be found in Goodison *et al*. (1998). However, only a fraction of the gauges have been operating concurrently; for instance in 2011 there were about 220 gauges measuring and reporting daily.

Form of precipitation

Observations of the form of precipitation done by the FMI were originally based on visual evaluation by an observer at the site. They were coded with a three-digit integer, each digit describing the form of precipitation recorded during 06:00–12:00 UTC, 12:00–18:00 UTC and 18:00–06:00 UTC, respectively. The FMI categorised weather into nine types (Table 1). In correction, some precipitation types had to be combined: 0 and 6 were treated as dry weather, 1 was not taken as rain and thus was not corrected, 2 and 7 were treated as rain, and 3, 5, 8 and 9 as snow. Sleet (type 4) was treated as 50% rain and 50% snow. If, for example, the code for a particular day was 502 and the amount of precipitation 12 mm, this was interpreted as solid precipitation of 4 mm recorded between 06:00 and 12:00 UTC, dry weather between 12:00 and 18:00 UTC, and liquid precipitation of 8 mm between 18:00 and 06:00 UTC. The amounts of precipitation were assumed to be proportional to the precipitation period lengths (in hours).

The FMI replaced the above-mentioned code in 2007 with a relation developed by Koistinen *et al*. (2004). It was derived using about 150 000 synoptic observations and discriminant analysis and can be expressed as follows:

$$P_{\mathrm{lp}} = \frac{1}{1 + e^{22 - 2.7T - 0.2H}} \quad (1)^*$$

where P_{lp} is the probability for liquid precipitation, T is the temperature (°C), and H is the humidity (%) at the height of 2 m. If P_{lp} is smaller than 0.2, precipitation is solid and if P_{lp} is greater than 0.8, precipitation is liquid. In the case of $0.2 \le P_{\mathrm{lp}} \le 0.8$ precipitation is treated as sleet.

Wind

Wind speed and direction measurements are cru-

* On 29 September 2016 the equation was corrected in the following way: 2.2T (in the denominator) was replaced by 2.7T.

cial for the aerodynamic correction, together with the exposure data of gauge sites. They are measured every third hour, being the most frequent observation needed for the correction procedure. Therefore, also correction was carried out using the same frequency by first adjusting precipitation, form of precipitation and temperature observations to the same periods. Several types of anemometers have been used since the beginning of the 1960s. Some of them provided only a rough estimate and the location of some devices was not reliable enough. In this study, only regionally representative wind speed and direction measurement stations defined by the FMI (*see* Fig. 1) were used because of their reliability and also because the aerodynamic correction method was developed for their data.

Metadata

In addition to the hydro-meteorological data, the metadata of the stations is needed for the correction of the precipitation observations. Besides the gauge type information, the registration of the height angle is crucial for the correction procedure in eight directions (45° sectors) from the gauge. The FMI has collected this information since 1961, dating the information every two or three years if necessary, but it is by no means comprehensive in terms of the number of gauges and time coverage, thus affecting the application of the method. Moreover, the height of the anemometer is needed in the case of missing exposure information when the wind speed during the storm is calculated.

Correction method of precipitation measurements

General

Because of the operational purpose of use, the correction of the precipitation measurements was carried out as a simplified version of the Finnish exposure method developed by Solantie (1986) based on the theory of Korhonen (1942). Sarkanen (1989) and Førland *et al*. (1996) also presented this approach. The overall correction scheme consists of three components: (1) aerodynamic, (2) wetting and (3) evaporation correction. The common expression for corrected precipitation P_c for the Nordic countries can be written as (Førland *et al*. 1996):

$$P_c = (1 + A) \times (P_m + \Delta P_w + \Delta P_e), \qquad (2)$$

where $1 + A$ is the aerodynamic correction, P_m is the measured precipitation, ΔP_w is the wetting correction and ΔP_e is the evaporation correction. These terms are explained in detail next.

Aerodynamic correction

Typically, a freely-exposed precipitation gauge systematically distorts the wind field, causing the wind speed to increase above the gauge orifice and forcing the development of eddies in and around the gauge. Therefore, smaller liquid and solid precipitation particles are prevented from entering the gauge. Wind speed can be considerably greater than the velocity of the fall-

Table 1. Codes for forms of precipitations used by the Finnish Meteorological Institute (FMI).

Code	Explanation	Weather
0	dry	haze, smoke, snow drift, glaze, no precipitation
1	humid	surface fog, mist, frost, rime, fog, dew
2	rain	drizzle, rain, shower, freezing drizzle, freezing rain
3	hail	small hail, frozen hail
4	sleet	sleet, sleet shower, ice pellets, rain with snow
5	snow	snow, snow shower, snow pellets, ice needles
6	thunder without rain	thunder without rain
7	thunder and rain	thunder and rain
8	thunder and hail	thunder and hail
9	thunder and snow or sleet	thunder and snow or sleet

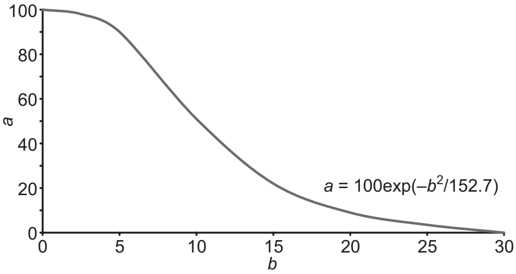

Fig. 2. Instantaneous exposure coefficient *a* as a function of the height angle *b* (°) of the objects surrounding the gauge (adapted from Sarkanen 1989).

ing particles, particularly snow, which results in slow-falling particles being carried beyond the lee side of the gauge orifice. Hence, the amount of observed precipitation is generally smaller than the non-biased precipitation. The loss of the measured precipitation increases with the proportion of small drops and light snow particles and with increasing wind speed (Sevruk 1989b).

The aerodynamic correction approach applied in this study is called the exposure method and it is developed particularly for conditions in which wind speed observations at the gauge are not available, but the weather data from the nearest synoptic station can be used instead (Solantie 1986). The aerodynamic correction factor (1 + *A*) depends on the wind speed and direction, precipitation type, falling speed of the drops and gauge type. The term *A* is called the relative aerodynamic correction and it consists of the wind correction k_w and the basic part k_c:

$$A = k_w k_c = (k_{we} k_{wa} k_{wi}), \tag{3}$$

Table 2. Basic factor k_c (adapted from Førland *et al*. 1996).

Precipitation type	Temp. (°C)	Basic factor k_c	
		Wild	Tretjakov and H&H-90
Drizzle	–	0.34	0.05
Rain	–	0.01	0.01
Sleet	$T \geq 0$	0.13	0.05
Snow	$-8 < T < 0$	0.28	0.18
Snow	$T \leq -8$	0.40	0.18
Shower	$T \leq 1$	0.28	0.18
Shower	$T > 1$	0.01	0.01

where k_{we} is the exposure factor, k_{wa} is the areal wind coefficient (= 1 in this application) and k_{wi} is the actual wind coefficient. The factor k_c depends on the precipitation and gauge type (Table 2).

In the wind correction, k_{we} is defined as

$$k_{we} = a/\bar{a}, \tag{4}$$

where $\bar{a}$ is the average exposure coefficient (= 35 in this application) and *a* is the instantaneous exposure coefficient. The latter coefficient is determined according to the wind direction during the storm observed at the nearest synoptic station, which is representative for the particular area and describes the wind shelter given by surrounding structures and trees to the gauge using the height angle *b*

$$b = \tan^{-1}(h_{obj}/d_{obj}), \tag{5}$$

where h_{obj} and d_{obj} are the height and distance of the sheltering object, respectively. When *b* has been obtained, *a* can be determined (Fig. 2). The relation is interpreted so that $a = 0$ indicates a fully sheltered and $a = 100$ a fully open gauge. All the main wind directions are treated separately.

The actual wind coefficient k_{wi} is expressed as

$$k_{wi} = w/\bar{w}, \tag{6}$$

where *w* is the wind speed during the storm and $\bar{w}$ is the long-term average wind speed calculated over all three hour observations, both obtained from the nearest synoptic station which is representative for the particular area.

If there is no exposure information for the rain gauge for the given time, the exposure method cannot be used and $k_{we} = 1$. This modification is called the wind method, in which the instantaneous wind speed and average wind speed are reduced. The reduction was carried out by the power law method (e.g. Schwarz *et al*. 2009):

$$w = w_1(z/z_1)^{0.143}, \tag{7}$$

where w_1 and z_1 are the reference velocity and reference height, respectively, and *z* is the height of the gauge orifice. The exponent 0.143, suggested by Schlichting (1968), is often cited in engineering texts for neutrally stratified boundary layers. This assumption is valid for long-lasting precipitation events or for events with hard wind. There may be some snowfall in stable conditions, but then wind speed is so small that the reduction error due to assumption can be neglected.

Wetting and evaporation correction

The wetting correction ΔP_w in Eq. 2 accounts for precipitation that has become attached to the inside walls of the precipitation gauge but is not included in the measured amount. It depends on the material of the gauge and the form of precipitation and is inversely proportional to the orifice area of the gauge. With the exception of 80% higher amounts for rain and snow in case of the Wild gauge (R. Solantie pers. comm.), the values used in this application (Table 3) are taken from Førland *et al*. (1996).

The evaporation correction ΔP_e estimates the precipitation that had evaporated from the gauge before the measurement has been taken. The values of the mean daily evaporation loss (Table 4) recommended by Førland *et al*. (1996) are added to the measured value according to Eq. 2. The fairly high values for the Tretjakov gauge in the spring are explained by the practice of using the gauge without a funnel during the cold period of the year. It is inserted in the summer, providing the collector with a good shelter from evaporation. The correction is made in periods of three hours when precipitation has occurred, and these values are adjusted correspondingly.

Results

The following analysis was carried out to evaluate the correction method and reliability of the results. Since a vast amount of very heterogeneous data was used and the end product enables wide-ranging usage, the aim was to give a thorough view of it and different related aspects of the correction process. Henceforth, the time interval from 1961 to 1981 when the Wild type gauges were used is called Period1, and the time interval from 1982 to 2011 when the Tretjakov and H&H-90 gauges were in operation is called Period2. The correction for both periods was carried out using the same method but with different parameter values.

A total of about 9 million daily observations 1961–2011 were included, among them about 4.4 million (49.3%) days with precipitation. The proportions of the forms of precipitation were 32.9%, 18.1% and 49.0% for solid, mixed and liquid, respectively.

Daily correction factor in different intensity classes and precipitation forms

First, histograms of the unitless correction factor for different precipitation intensity classes were examined. Both total precipitation and different forms were considered (Fig. 3). For the sake of clarity, the distributions were cut at 4.0, even though there were higher values, but it did not change their shape. The distribution of the correction factor varied clearly depending on the form of precipitation within each intensity class excluding < 1 mm day^{-1} (Fig. 3e–h); the mode of distribution was smaller and its occurrence more

Table 3. Wetting correction amounts (mm/case).

Precipitation type	Wild	Tretjakov	H&H-90
Rain	0.126	0.140	0.130
Drizzle	0.050	0.120	0.090
Snow	0.054	0.090	0.050
Mixed	0.070	0.140	0.110

Table 4. Evaporation correction amounts (mm per day).

Month	Wild	Tretjakov	H&H-90
January	0.01	0.03	0.03
February	0.02	0.04	0.04
March	0.03	0.05	0.06
April	0.01	0.22	0.20
May	0.01	0.13	0.04
June	0.01	0.15	0.05
July	0.01	0.15	0.05
August	0.01	0.10	0.05
September	0.01	0.05	0.04
October	0.01	0.03	0.03
November	0.00	0.03	0.03
December	0.00	0.03	0.03

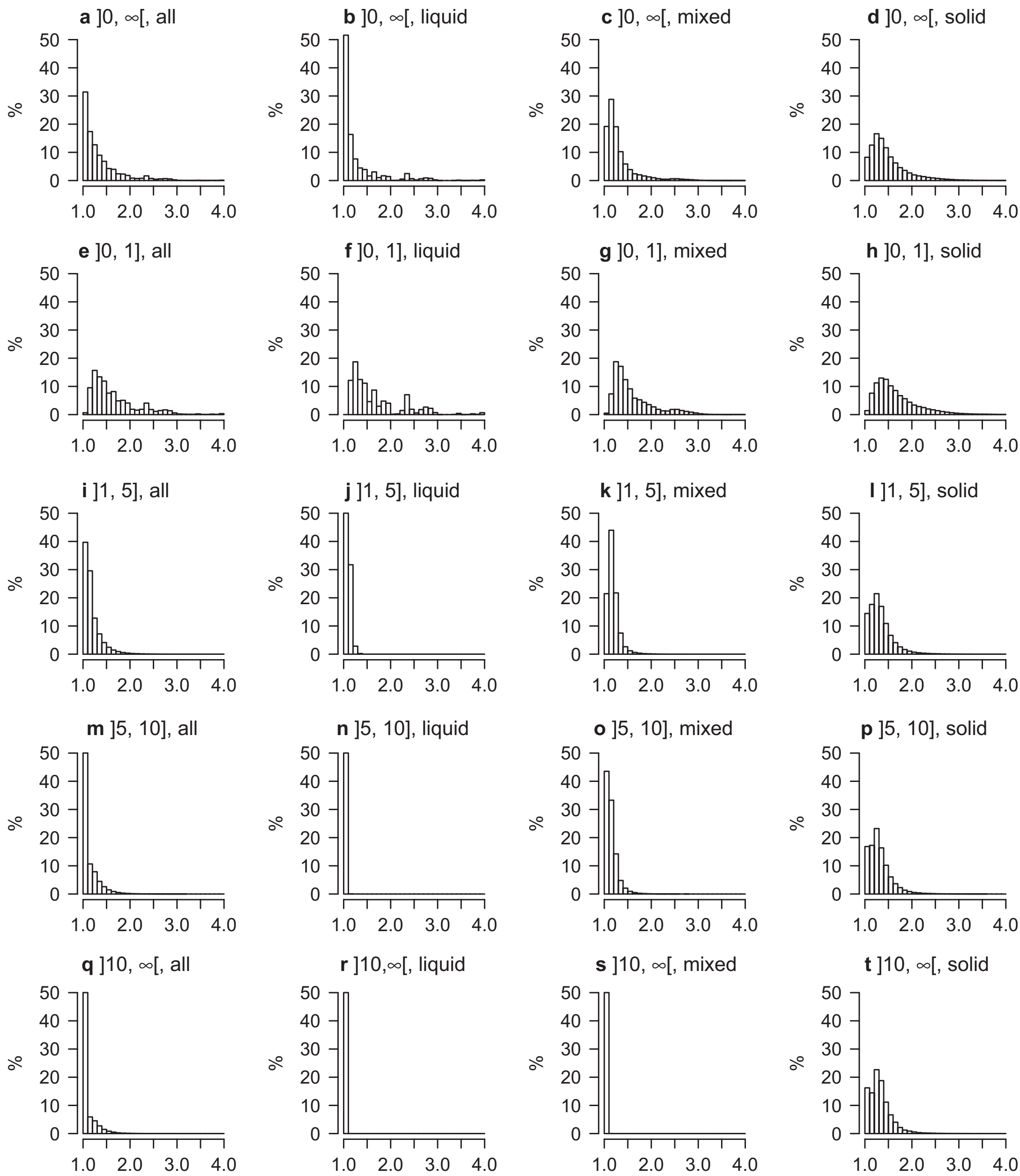

Fig. 3. Histograms of correction factor in different intensity intervals (in rows) and form classes (in columns) of observed precipitation (mm day^{-1}).

frequent for liquid than for solid precipitation. On the other hand, the liquid form got high correction factor values with very small precipitation (Fig. 3f). The distribution of the correction of the solid precipitation did not vary considerably with intensity (Fig. 3h, l, p and t). The correction factor of liquid precipitation was virtually 1.0–1.05 for higher intensities (> 5.0 mm) (Figs. 3n and r).

Next, the 10th, 25th, 50th, 75th and 90th percentiles of the correction factor for different intervals and form classes of observed precipitation were studied (Table 5). The medians (50th percentiles) of all precipitations in a way summarise the correction on daily basis; the corrections for all forms, liquid, mixed and solid precipitation in general were 1.21, 1.10, 1.21 and 1.39, respectively. Also on a general basis, the higher the percentile, the greater the difference of the correction factor between the forms. In more detail, in each interval and percentile, the correction factor of the solid form was greater than the one of the mixed form, which was greater than the one of liquid form, with the exception of the precipitation interval]0, 1] and higher percentiles. These cases occurred during spring and summer and were caused by the high proportion of evaporation correction.

Amounts of correction components

The overall average amount of correction was 79.9 mm per year, equivalent to 11.9% of the total corrected precipitation, and the reciprocal proportions were 8.6%, 22.8% and 68.6% for evaporation, wetting and aerodynamic corrections, respectively (Table 6). The aerodynamic correction was clearly greater and the evaporation correction smaller in Period1 than in Period2. Also the total amount of correction was greater in Period1. The proportion of aerodynamic correction of the total correction (83.3%) was remarkably high when solid was the most typical from of precipitation (December–March). It was clearly greater in Period1 (89.1%) than in Period2 (77.1%). In May–September, the corresponding proportions were 38.8% and 23.3%. In April–August, when evaporation correction has a more notable role, the different correction types were almost equal in Period2. In Period1, the role of evaporation was minor.

Obviously, there was a great variation in the monthly mean aerodynamic correction (Fig 4). It can be almost as large as the mean in winter months. In December–March, the amounts of the aerodynamic correction were 8.6–12.0 mm and 5.6–7.9 mm for Period1 and Period2, respectively. The average total amounts of the correction for the same months were 10.0–13.2 mm and 7.6–9.9 mm for Period1 and Period2, respectively. The average aerodynamic correction amounts in May–September were 0.7–1.8 mm and 0.7–1.1 mm for Period1 and Period2, respectively.

Table 5. Percentiles of correction factor in different intensity intervals and form classes of observed precipitation (mm day^{-1}).

Precipitation intensity (mm day^{-1})	Form of precipitation	Percentiles of correction factor				
		10th	25th	50th	70th	90th
]0, ∞[	all	1.035	1.075	1.209	1.467	1.905
	liquid	1.026	1.043	1.095	1.292	1.830
	mixed	1.069	1.119	1.209	1.375	1.740
	solid	1.117	1.227	1.385	1.643	2.040
]0, 1]	all	1.200	1.296	1.493	1.870	2.410
	liquid	1.191	1.272	1.467	1.900	2.560
	mixed	1.214	1.294	1.450	1.790	2.360
	solid	1.211	1.338	1.545	1.878	2.333
]1, 5]	all	1.050	1.073	1.124	1.239	1.416
	liquid	1.046	1.058	1.082	1.116	1.151
	mixed	1.070	1.108	1.161	1.233	1.327
	solid	1.073	1.164	1.283	1.436	1.642
]5, 10]	all	1.025	1.032	1.045	1.138	1.317
	liquid	1.024	1.029	1.035	1.043	1.053
	mixed	1.036	1.069	1.113	1.192	1.288
	solid	1.049	1.156	1.266	1.410	1.601
]10, ∞[	all	1.013	1.018	1.025	1.043	1.216
	liquid	1.013	1.017	1.022	1.028	1.035
	mixed	1.026	1.058	1.106	1.191	1.288
	solid	1.048	1.169	1.286	1.420	1.602

Table 6. Average corrections for evaporation, wetting and aerodynamic losses per year for mainly snow, rain and evaporation periods.

Period	January–December, liquid and solid precipitation			December–March, mainly solid precipitation			May–September, mainly liquid precipitation			April–August, large evaporation correction		
	Amount (mm)	Percentage of correction	Percentage of precip.	Amount (mm)	Percentage of correction	Percentage of precip.	Amount (mm)	Percentage of correction	Percentage of precip.	Amount (mm)	Percentage of correction	Percentage of precip.
1961–2011												
Evaporation	6.9	8.6	1.0	1.8	4.5	1.0	3.1	18.7	1.0	4.0	19.8	1.4
Wetting	18.2	22.8	2.7	4.9	12.3	2.6	8.7	51.9	2.7	7.8	38.8	2.7
Aerodynamic	54.8	68.6	8.2	33.3	83.3	17.8	4.9	29.4	1.6	8.3	41.4	2.9
Sum	79.9	100.0	11.9	40.0	100.0	21.4	16.7	100.0	5.3	20.1	100.0	6.9
Period1												
Evaporation	1.9	2.1	0.3	0.9	1.9	0.5	0.7	4.6	0.2	0.6	3.5	0.2
Wetting	16.7	18.8	2.5	4.2	9.0	2.3	8.3	56.5	2.7	7.3	39.5	2.6
Aerodynamic	70.5	79.1	10.7	41.3	89.1	23.2	5.7	38.8	1.9	10.5	57.0	3.8
Sum	89.1	100.0	13.6	46.4	100.0	26.1	14.6	100.0	4.8	18.5	100.0	6.7
Period2												
Evaporation	10.6	14.8	1.5	2.5	7.1	1.3	4.9	27.0	1.5	6.4	30.8	2.1
Wetting	19.3	26.9	2.8	5.4	15.8	2.8	8.9	49.6	2.7	8.1	38.9	2.7
Aerodynamic	41.8	58.3	6.1	26.6	77.1	13.5	4.2	23.3	1.3	6.4	30.4	2.1
Sum	71.6	100.0	10.5	34.5	100.0	17.5	18.0	100.0	5.5	20.9	100.0	7.0

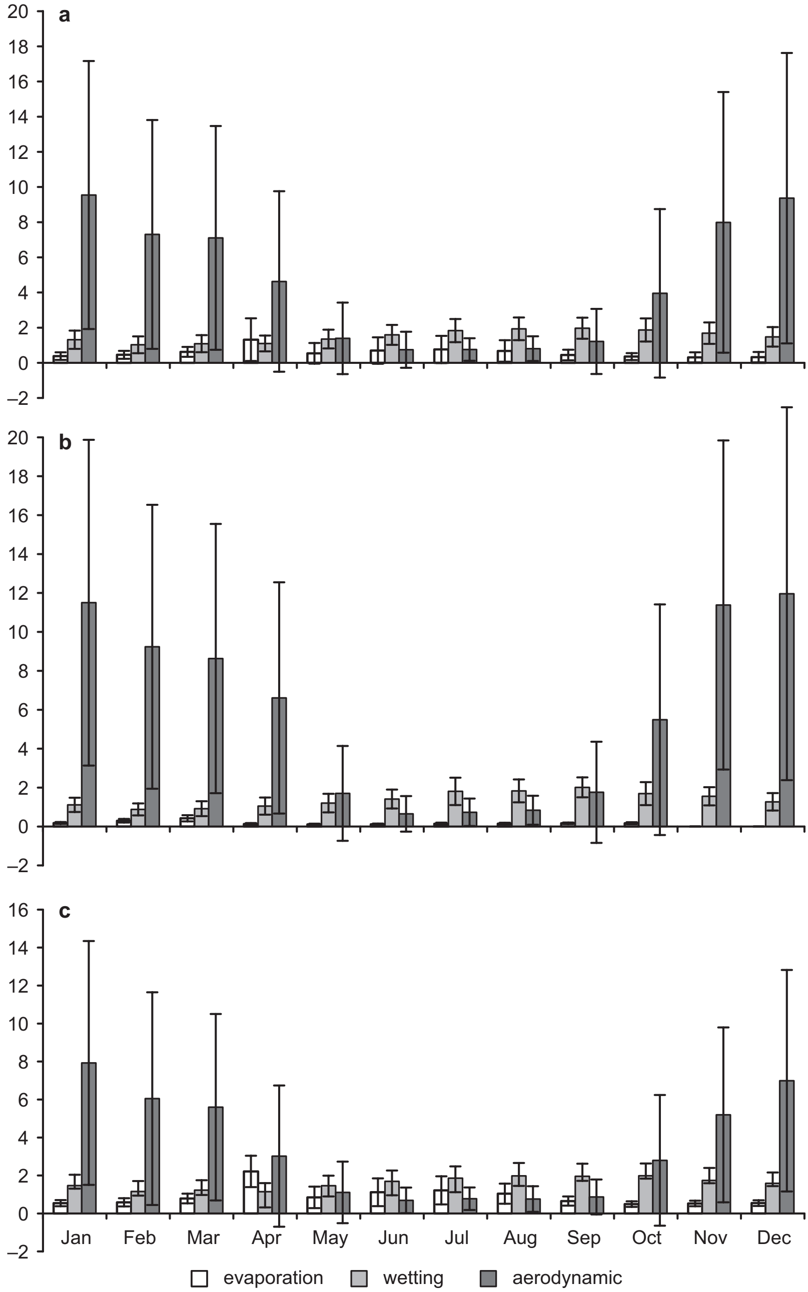

Fig. 4. Mean monthly amounts (± SD, mm) of correction components. (**a**) 1961–2011, (**b**) Period1, and (**c**) Period2.

In April–August, the different amounts of evaporation correction were emphasised. They were 0.1 mm and 0.8–2.2 mm for Period1 and Period2, respectively. Wetting correction varied least through the months and between the periods, the ranges being 0.9–2.0 mm and 1.1–2.0 mm for Period1 and Period2, respectively (Fig. 4b and c).

Effect of exposure information

To understand the effect of exposure information of the gauges on correction amounts, the same set of data was corrected by both exposure and wind methods. The data set consisted of the period 1961–1999 and 75 gauges, including

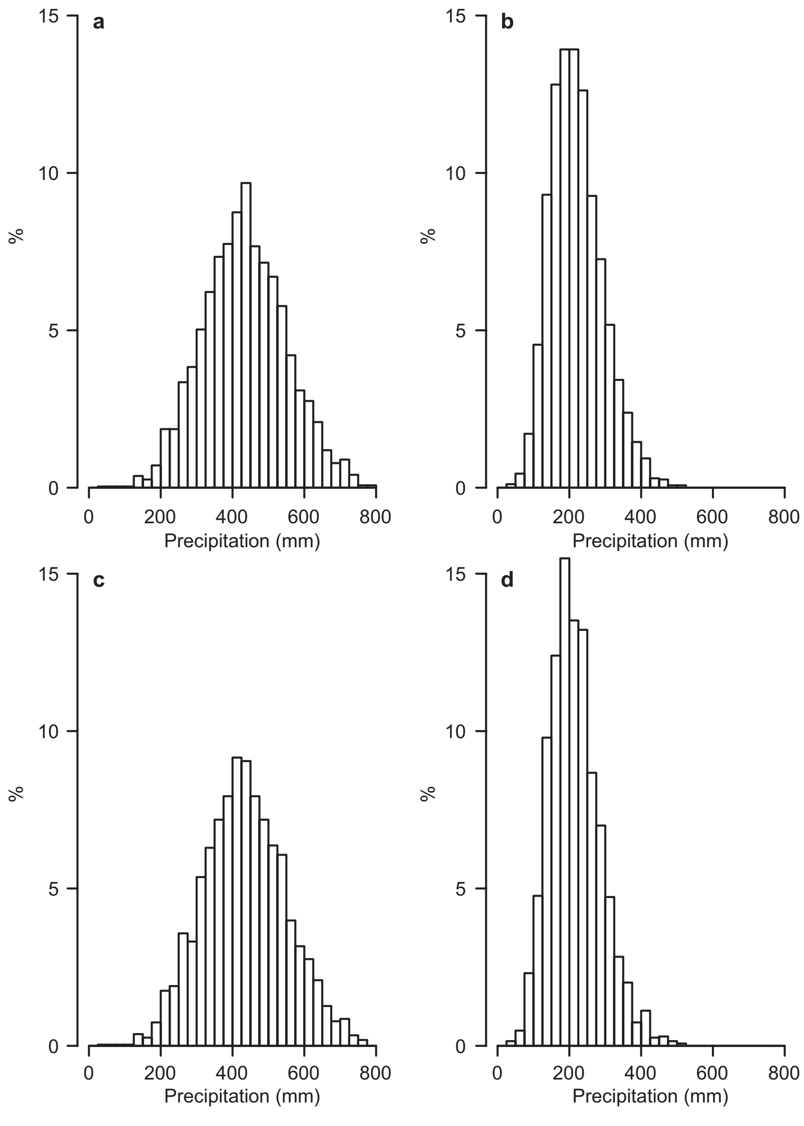

Fig. 5. Histograms of yearly precipitation sums of 75 gauges in 1961–1999: (**a**) liquid precipitation corrected by the wind method, (**b**) solid precipitation corrected by the wind method, (**c**) liquid precipitation corrected by the exposure method, and (**d**) solid precipitation corrected by the exposure method.

the Wild, Tretjakov and H&H-90 types, with reliable exposure information. In case of liquid precipitation (Fig. 5a and c), the distributions of the corrected yearly sums seem quite similar. The means of liquid precipitation sums corrected by exposure and wind methods were 433.5 mm (SD = 115.0 mm) and 433.9 mm (SD = 115.2 mm), respectively. When statistically tested (paired *t*-test assuming unequal variances, e.g. Milton and Arnold, 1987) they differed significantly (t_{2685} = 2.7605, p = 0.00581). In case of solid precipitation, the distributions differed more clearly (Fig. 5b and d). The means were 216.0 mm (71.4 mm) and 220.6 (72.4 mm) for exposure and wind methods, respectively. Paired *t*-test assuming unequal variances ($t_{2685} = 6.7384$, $p = 1.952 \times 10^{-11}$) also showed clear evidence of the difference.

Regional distributions of annual precipitation sums

There are some characteristic places in Finland in terms of precipitation (Fig. 6a), which should be mentioned when precipitation maps, obtained by calculating areal precipitation to

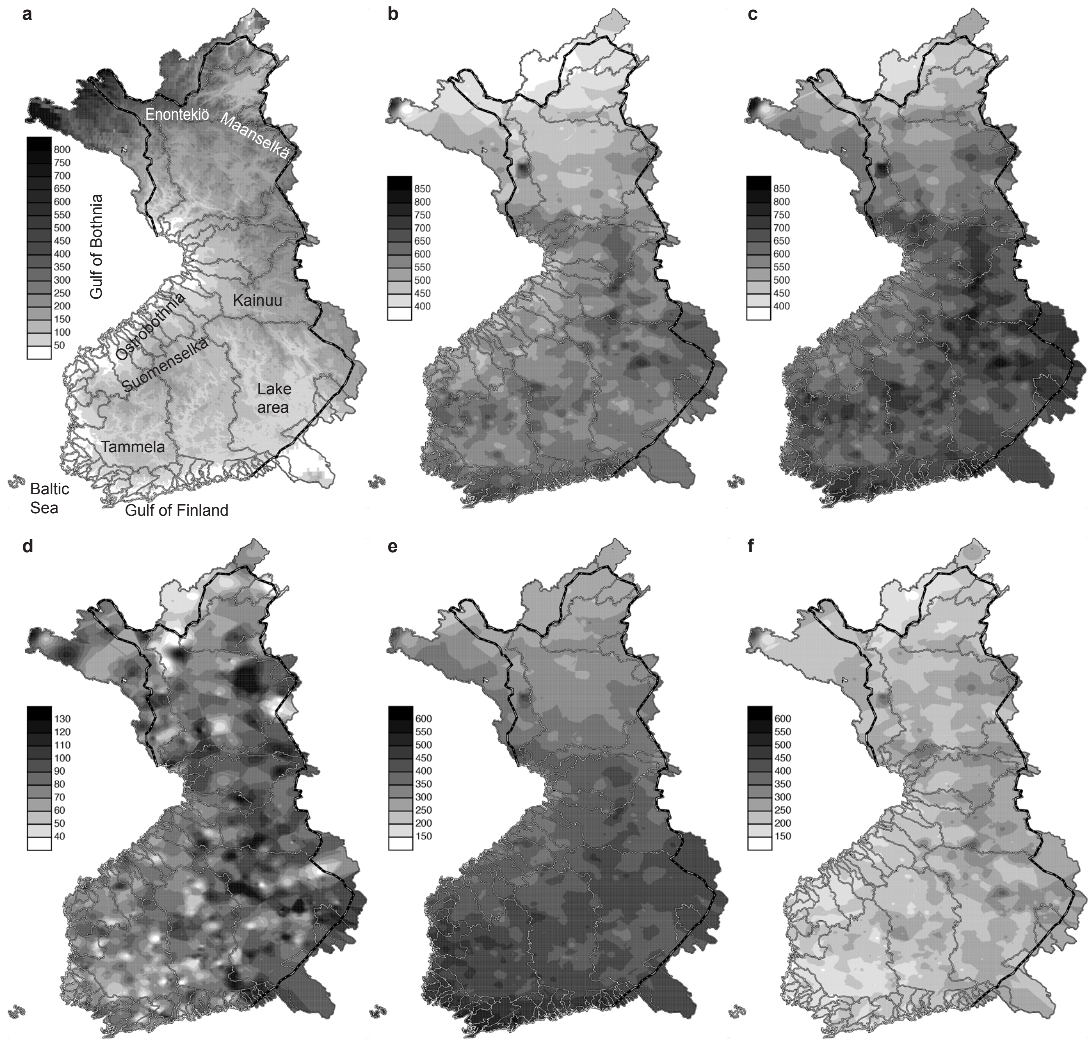

Fig. 6. Spatial variation of annual mean precipitation (mm) in Finland: (**a**) regions, (**b**) observed, (**c**) total corrected, (**d**) total corrected – observed, (**e**) corrected liquid, and (**f**) corrected solid. The areas in the background are the main watershed boundaries.

a 1 × 1 km grid by inverse distance squared method using the three nearest point-wise observations (Fig. 6b–f), were analysed. Minimal spatial smoothing between grid cells was used to study the effects of different gauges. All the distinguishable spots were checked. In some cases, a gauge was located in such an open place that it was exposed to winds and much higher aerodynamic correction was carried out in comparison with the surrounding gauges. However, there were also cases when measurements of a gauge were found to be unreliable and were removed from the data.

The general patterns of the observed (Fig. 6b) and corrected (Fig. 6c) precipitation were increasing towards the east and south of Finland. This was more emphasized in corrected amounts. Of course, there were local anomalies from this pattern due to exposure and wind conditions. The general pattern of difference between corrected and observed precipitation (Fig. 6d) followed the one of the solid precipitation (Fig. 6f). Liquid precipitation (Fig. 6e) was greater than solid precipitation. Moreover, the areal distribution of precipitation was different in the winter and summer halves of the year. In winter, the Scandinavian mountains dried out the precipitation areas coming from west with the result of increasing the precipitation in Finland about 5% per 100 km towards the south-east of the country. Other areas with high solid precipitation (300–350 mm) were the Maanselkä area, the eastern ends of the Suomenselkä and particularly the Enontekiö area. There were also local spots of high amounts of solid precipitation outside these areas. On the other hand, the coast of the Gulf of Bothnia, the Ostrobothnia area between the coastline and Suomenselkä, and south–west Finland were the areas with the least solid precipitation (150–200 mm).

Overall, the total regional yearly sum was composed of liquid and solid totals. The maximum was located in the same place as the solid maximum, and the minimum in the same place as the liquid minimum. The features of the above-mentioned distribution of solid and liquid precipitation stand out better in the maps of total sums, for instance the tendency of increasing solid precipitation from north-west to south-east and the higher amounts close to the watershed divides. These phenomena were more emphasised with the corrected precipitation (Fig. 6c).

Long-term time series and linear trends of annual sums

Considering the effect of correction for all gauges and the whole period, the total annual precipitation increased 13.6% from 590.3 mm to 670.6 mm. The proportions for liquid and solid precipitation were 63.6% and 36.4%, respectively (Table 7).

The long-term analysis of annual sums of observed and corrected precipitation (total, solid and liquid) was carried out separately for the whole period, Period1 and Period2. The year 1982 was omitted since the replacement of the Wild gauges by the Tretjakov gauges took place during that time. Obviously, the variation of the corrected total was greater than that of the observed precipitation (Fig. 7a and b), particularly the large values are more frequent with the corrected total. The differences of means between the periods were statistically tested using Student's *t*-test for unequal variances (*see* e.g. Milton and Arnold 1987) and were found statistically highly significant which indicates that the observed, corrected total and corrected liquid precipitation were greater and corrected solid precipitation smaller in Period2 (Table 7).

The statistics of linear trend analysis was based on the least square method of slope fitting (Table 8). In the whole period, the trends were found in all parameters, three of them being positive and the one for the solid precipitation negative. In Period1, the trends in all parameters were positive trends, whereas in Period2 the trend was positive for liquid precipitation only and negative for both corrected total and corrected solid precipitation, with observed precipitation having no trend at all.

Validation using a hydrological model

First, appropriate metrics for assessing the goodness of precipitation correction was defined. A common metrics in hydrological modelling, coefficient of determination r^2 (also known as Nash-Sutcliffe model efficiency), was calculated for the observations and simulations of WSFS discharge simulations. We found out that comparing r^2 values from runs with uncorrected and corrected precipitation data gave a clear indicator of the goodness of precipitation correction in terms of water balance. To distinguish the

Table 7. Mean annual precipitation sums (mm) for 1961–2011, Period1 and Period2 and results of the *t*-test for unequal variance comparing Period1 with Period2.

	1961–2011	Period1	Period2	df	t	p
Observed	590.3	566.4	611.5	20 687.1	–29.0528	$< 2.2 \times 10^{-16}$
Corrected total	670.6	657.4	683.5	20 072.4	–15.0952	$< 2.2 \times 10^{-16}$
Corrected liquid	439.6	418.2	458.2	21 862.3	–27.9645	$< 2.2 \times 10^{-16}$
Corrected solid	231.0	239.2	225.3	20 988.7	13.6527	$< 2.2 \times 10^{-16}$

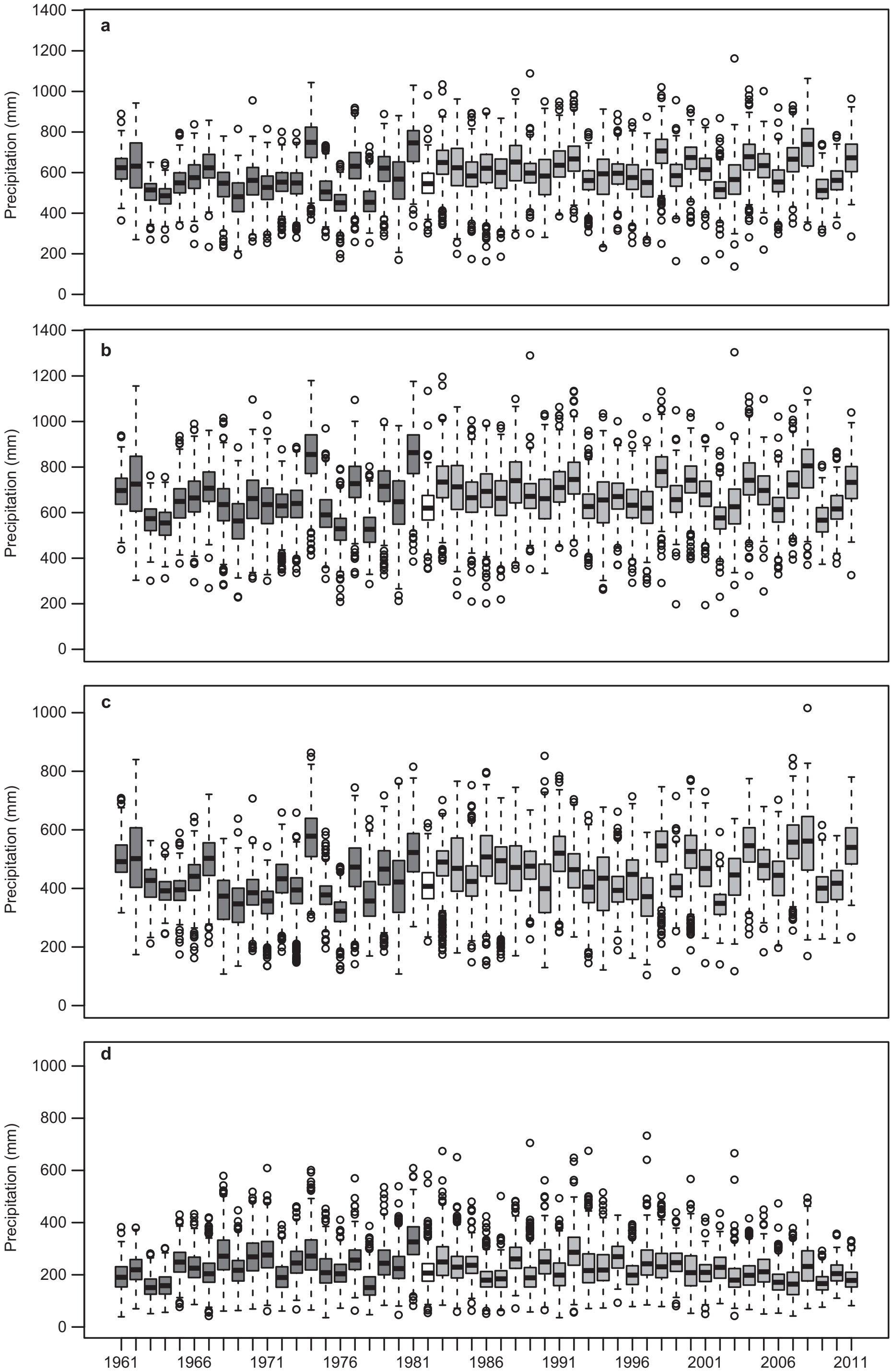

Fig. 7. Time series of annual precipitation (mm) distribution: (**a**) observed, (**b**) total corrected, (**c**) corrected liquid, and (**d**) corrected solid. Dark grey boxes indicate Period1, light grey boxes Period2, and the white box the gauge exchange year 1982. The horizontal line within the box indicates the median; the bottom and top of the box the 25th and 75th percentiles, respectively; the upper whisker shows 1.5 times the interquantile range or maximum value, whichever is the smaller, and the lower whisker 1.5 times the interquantile or minimum value, whichever is the greater; circles are outliers.

Table 8. Statistics of long-term analysis of annual precipitation. Estimates set in boldface, italic and underlined indicate positive, negative and no trend, respectively.

Parameter	1961–2011				Period1				Period2			
	Estimate	SE	t	p	Estimate	SE	t	p	Estimate	SE	t	p
Observed	**1.687**	0.060	28.24	< 0.0001	**3.106**	0.231	13.43	< 0.0001	–0.142	0.124	–1.15	0.2521
Corrected	**0.905**	0.067	13.59	< 0.0001	**3.501**	0.264	13.24	< 0.0001	*–1.056*	0.134	–7.87	< 0.0001
Liquid	**1.509**	0.056	27.12	< 0.0001	**1.827**	0.204	8.95	< 0.0001	**0.280**	0.122	2.30	0.0213
Solid	*–0.604*	0.039	–15.62	< 0.0001	**1.674**	0.148	11.29	< 0.0001	*–1.336*	0.081	–16.58	< 0.0001

r^2 difference due to uncorrected and corrected precipitation, r^2 values were calculated only for the period 1 March–20 June in 26 years determined by the WSFS calibration procedure. This is because the correction for solid precipitation is much greater than for liquid precipitation and cumulative precipitation during winter strongly affects spring flood discharge simulation and therefore differences in r^2 are greater in spring than in other seasons.

The r^2 metrics simulations were run with precipitation input produced by four methods: (1) traditional correction, (2) daily correction, (3) observed precipitation, and (4) daily correction with fitted coefficients. *Traditional correction* refers to method used in WSFS in which fitted areal coefficients for both liquid and solid precipitation are determined and division to solid and liquid precipitation was done with fitted areal temperature limit values. Coefficients and limit values were fitted to minimize the difference of simulated and observed discharge, which will give the traditional method an edge over daily correction method when compared with r^2 metrics. *Daily correction method* is the method described in this article. When using *measured precipitation*, the form of precipitation is determined by observations and the precipitation volumes are not corrected but plain gauge observations are used. The method of *daily correction with fitted coefficients* is a combination of daily correction method and traditional correction method: fitted areal coefficients for both liquid and solid precipitation are applied to precipitation corrected by the daily method.

There was no substantial difference between the daily and traditional correction methods (*see* Fig. 8a). The histogram is slightly tilted in favour of the traditional method which, however, is expected due to fitted coefficients and temperature limit values. Using daily corrected precipitation results in greater r^2 in most discharge stations than using plain observations (Fig. 8b). The r^2 differences between the traditional correction and the daily correction with fitted coefficients are depicted in Fig 8c. Superiority of either method is not obvious, but the results resemble the ones presented in Fig. 8a. However, it must be noted that using daily corrected precipitation with fitted coefficients instead of traditional

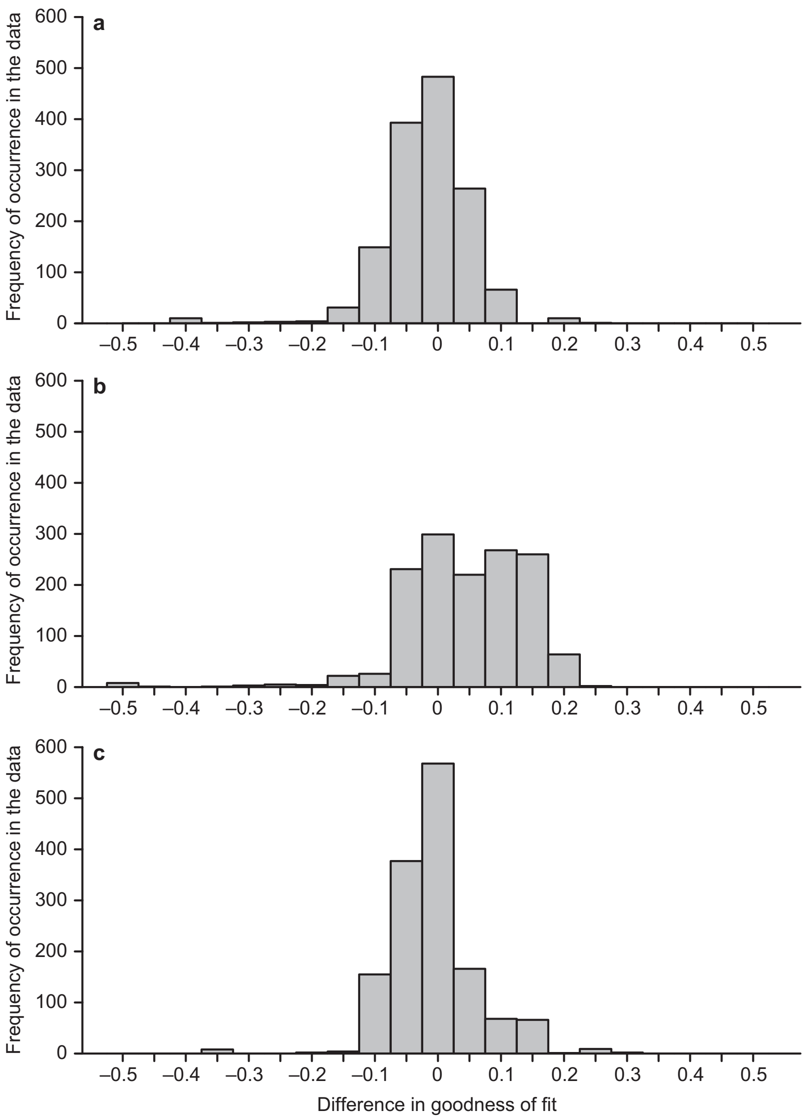

Fig. 8. Histograms of differences in goodness of fit (r^2) of hydrological model simulations with precipitation inputs from: (**a**) daily correction – traditional correction, (**b**) daily correction – observed precipitation, and (**c**) daily correction with fitted coefficients – traditional correction.

method increased the goodness of fit more than 0.10 for some discharge stations. Comparison of Fig. 8a and c indicates that using areal fitted coefficients with daily correction is beneficial.

To validate the correction factor of daily correction method, we examined the respectively fitted areal coefficients, which alter the precipitation input to better match the water balance based on discharge observations (Fig. 9). Coefficients below 1 indicate that the daily correction method is correcting the volume of precipitation too much and coefficients above 1 indicate a too small daily correction.

Discussion

The focus of this study, outlined on the basis of operational hydrological modelling in which every observation is valuable if it is reliable, was to check the correction procedure and estimate the amount of correction in total precipitation and in liquid and solid forms. The correction method was selected so that it suits well the Finnish conditions and uses standard hydro-meteorological observations readily available for the whole study period. Data were heterogeneous due to changes in gauge network, a number of gauge and instrument types,

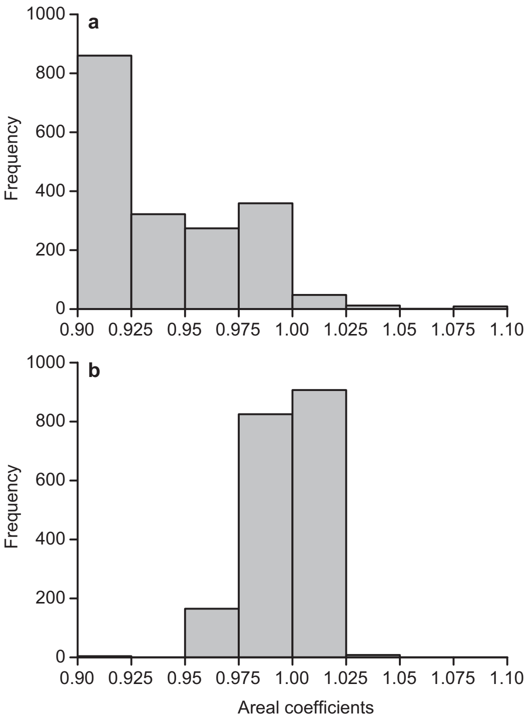

Fig. 9. Histograms of areal coefficients for (**a**) solid and (**b**) liquid precipitation fitted with the corrected precipitation to match the water balance based on discharge observations.

countries and practices, exposure, geographical and climatic conditions, etc. The principle of synchronising precipitation, wind and form of precipitation observations suits well with stable weather conditions but can bring on errors with unstable conditions such as cold fronts and showers. Moreover, daily mean temperature value is too rough for many weather situations since temperature can vary significantly during a 24-hour period. Using only reliable, regionally representative wind stations guarantees that the general weather type is well described and thus supports areal precipitation calculations, but diminish sensitivity to adapt to spatial variation. Allerup *et al*. (2000) stated that in Danish conditions wind observations can be extrapolated from remote sites not farther away than approximately 50 km. It is unknown how this applies to Finnish conditions but we estimated that approximately in 75% of all cases this instruction could be complied.

Wagner (2009) stated, based on literature review and questionnaire, that most precipitation data are still not systematically corrected. There are also very few published studies about operational and automatic precipitation corrections concerning all observations or observations from many decades with large spatial dimensions of a certain country or weather services institute. Most often, a limited number of gauges and/or homogenous conditions are selected, e.g. 12 stations in Greenland 1994–1997 by Yang *et al*. (1999), a few gauges in Norwegian Arctic by Førland and Hanssen-Bauer (2000), drifting stations in the Russian North Pole 1950–1990 by Bogdanova *et al*. (2002), five stations in high-latitude regions from three winters by Sugiura *et al*. (2006). The lack of operational corrections is probably due to considerable amount of data processing needed. Moreover, conditions can vary a lot and therefore a suitable method is not easily found, particularly for solid precipitation. Some of the very few studies found in the literature regarding long-term nationwide precipitation correction were the ones obtained by Lapin and Šamaj (1991) for a network of about 700 gauges in Slovakia 1981–1988 and Ye *et al*. (2004) for 710 stations in China 1951–1998.

Most studies comparing the corrected and observed precipitation are carried out for monthly or yearly sums even though in operational hydrology the usage of the measurements takes place often on a daily level. In one of the few assessments of daily amounts, Yang *et al*. (1998) stated that small absolute differences of measurements can result in large variations in catch ratios in daily precipitation. Therefore, in their analysis they only accounted for amounts greater than 3.0 mm per day, and concluded that the undercatch was always greater for solid than for liquid or mixed precipitation. Legates *et al*. (2005) found out that Arctic precipitation correction carried out using daily data are significantly more accurate than those based on monthly data because the daily meteorological data are more representative of the actual conditions when precipitation occurred. The results of this study showed that liquid form gets higher correction factor values more often. This obviously is due to the greater evaporation correction during the summer months. The relative effect of evaporation correction, as well as the one of the wetting correction, is particularly substantial with low precipitation intensities (< 0.2 mm h^{-1}). The correction of the solid precipitation occurs in a different way; it does not vary significantly with intensity because of its strong dependence on the aerodynamic correction. Instead, in cold weathers ($T \leq -8$ °C) it tends to get greater correction due to light snowflake.

Different correction methods, observation instruments and weather and climate conditions can produce remarkably different results for the corrected amount of precipitation and therefore comparing results obtained in this study with those of others' can only be done on a very general level. For example, Yang (1999) obtained 256 mm and Bogdanova *et al*. (2002) 165 mm for annual average corrected precipitation of Russian North Pole drifting stations in 1957–1990. At Alaska, correcting the Canadian Nipher gauge data Benson (1982) reported a correction factor, without considering wetting loss and trace amounts, of 1.1 and 3.5 for liquid and solid precipitation, respectively. Legates and Willmott (1990) presented monthly based climatological correction factors and, for instance, for Finland on January 1999 (virtually solid precipitation) they were greater than 1.5. Fuchs *et al*. (2001) showed similar values, estimated by an event-based method, for the south coast of Finland and Enontekiö area in the north but somewhat smaller values (1.1–1.5) for other areas. Yang *et al*. (1998), correcting wetting loss before dealing with the wind-induced errors, indicated an overall correction factor of 1.2 and 1.9 for liquid and solid precipitation, respectively. Metcalfe *et al*. (1994) corrected the snow data and the results indicated that the total corrected annual precipitation was 50%–100% greater than the gauge-measured yearly total. As for the Tretjakov gauges, also Sevruk (1982), Groisman *et al*. (1991) and Yang *et al*. (1995) demonstrated that the correction for snowfall is greater than that for rainfall. Førland *et al*. (1996) found a catch ratios of 0.95 and 0.7 for liquid and for solid precipitation, respectively, in their study with Nordic gauges. Førland and Hanssen-Bauer (2000) found a ratio between corrected and measured precipitation of 1.26 and 1.70 for the summer and winter seasons, respectively, in Norwegian Arctic. Yang and Ohata (2001) applied several corrections methods for Tretjakov gauges in Siberian regions in 1986–1992. Wind-induced undercatch was found to be the greatest error and the annual precipitation was found to increase 10%–65% due to correction. Adam and Lettenmaier (2003) showed 18.3% increase in mean annual precipitation for latitudes 60°–70°N in Eurasia using their systematic bias adjustments. Zhang *et al*. (2004) concluded that the corrected annual precipitation was 17%–42% higher than those measured and corrections were found to be higher in winter than in summer time in Mongolia. The wind loss was 5%–30% and wetting loss 3%–9% of the total correction. The evaporation loss was 4%–11%, which is slightly higher than 2%–8% found by Groisman *et al*. (1991) for Siberian conditions. Sugiura *et al*. (2006) stated 53.9% catch ratio for solid precipitation.

Also this study showed an obvious difference between liquid and solid precipitation forms in monthly and yearly sums. The correction of solid precipitation was particularly emphasized in cold weathers and strong winds from unsheltered directions. The proportions between corrected and observed amounts, as well as different components, were well within the ranges reported in the literature. The aerodynamic correction being the biggest, according to both this and other studies, emphasizes the influence of the method used. In practice, it is difficult to avoid placing precipitation gauges in locations with surrounding obstacles such as bushes, trees and buildings. At the same time in operational hydrology, there often is a shortage of information. Therefore, the exposure method presented and applied in this study can compensate many of the deficiencies or rectify errors and provide reliable precipitation information. There are only a few surveys (e.g. Solantie 1986, Førland *et al*. 1996) reporting usage of exposure information of the gauges when correcting precipitation observations. In this study, utilization of this information was found important and caused statistically significant difference in results on a general level. The differences were analysed in a long period (1961–1999) using 75 gauges without paying attention to the direction of the wind during the precipitation event so it can be assumed that there were a lot of occasions both in sheltered and unsheltered wind conditions.

The general patterns of the precipitation maps were found to be in strong correspondence with the ones presented in Solantie (1987). The precipitation amounts were higher in summer than in winter due to the showery nature of the rainfall and higher moisture content of the atmosphere then. It is also possible that some heavy snow or sleet showers occurring near 0° were interpreted as liquid precipitation. Anyway, the influence of this phenomenon should be marginal not causing bias in general patterns. The absolute amount of correction increasing towards the east of Finland, particularly in the southern parts, can be explained by the fact that the observed precipitation and thereafter the corrected precipitation is increasing even more strongly. The orographic conditions showed an important role during winter months since the rain clouds were low, stated also by Solantie (1987) and Solantie and Pirinen (2006). This explains the higher solid precipitation amounts in the areas of watershed divides, e.g. in the Salpausselkä area and in the higher ground of Tammela. On the other hand, during the summer half of the year, orography has virtually no effect on the regional distribution of precipitation, since the rainclouds are so high. However, the heat characteristics of land and water are significant, particularly in inland areas. In the afternoons, there is a tendency for rising currents above warm land surfaces, leading to showers and therefore liquid precipitation amounts are typically higher in inland than in other areas (Solantie 1987). However, due to the long-term averaging and because all the precipitation does not have this nature, the scattered effect of showers is not obvious in the lake area, but can easily be seen in the vicinity of the southern coast line. During the summer, the sum effect of central Finland, being on the route of lows moving from west to east and surrounded by sea and lakes, causes maximum liquid precipitation in Suomenselkä, the lake area and Kainuu. The similarity between the difference of corrected and observed precipitation and the corrected solid precipitation patterns was due to the fact that the correction of solid precipitation was greater. Corresponding regional patterns can be recognized in many snow related records, like solid form precipitation as percentage of total precipitation, snow depth with a rare occurrence (Solantie 1987), winter month precipitation amounts (Pirinen *et al*. 2012), snow zones (Solantie *et al*. 1996) and also from some temperature related records, such as the annual range of monthly mean temperatures (Helminen 1987). Instead, similarity with regional wind patterns is not obvious, apart from the SE corner of Finland which is prone to winds from the direction between west and south (Helminen *et al*. 1987). The effect of winds depends on the exposure conditions of the gauge, for instance even strong winds can results in minuscule correction if the gauge is sheltered from the direction of wind. The effect of wind can also be difficult to distinguish from the general climate patterns because the wind direction during the precipitation event (measured every third hour) can vary and gauges may have different exposure conditions in each direction.

Even though statistically significant trends were found in terms of different periods and precipitation forms, a stand, based solely on this study, cannot be taken on whether they are due to changes in gauge types, gauge network, correction method, climate, etc., or a combination of these. The results are also not representative averages for Finland since the spatial distribution of gauges is not even throughout the country (Fig. 1). When studying changing climate in particular, a representative group of gauges with carefully analysed metadata should be selected and used only in the analysis, as was done by Pirinen *et al*. (2012).

Saltikoff *et al*. (2015) compared radar based estimates of solid precipitation with the corrected solid precipitations of this study. They found that their average ratio was 1.59 for the entire data set. The ratio depended on the precipitation intensity: the weaker the intensity was, the greater the ratio. This was most common for precipitation below 2 mm per day. On the other hand, in moderate and high-intensity precipitation, they found cases in which corrected precipitations were greater than the radar-based estimates. The ratio varied with the distance to the radar so that at shorter ranges radar precipitation was typically greater than the corrected precipitation but beyond 150 km the radar gave increasingly smaller values.

In the assessments with the watershed scale hydrological model, we found that using the corrected precipitation instead of plain observed precipitation improved the goodness of fit of the model (r^2), and using the fitted coefficients with daily correction improved it even more. However, using either the traditional method or the correction method of this study with fitted coefficients did not make significant difference. The fact that no clear distinction in r^2 values was found means that it is worthwhile to use the corrected precipitations with areal fitted coefficients as the input for the hydrological model, because, in principle, they are more realistic, taking into account the ever-changing weather circumstances at gauges. Our findings are consistent with the ones of Stisen *et al.* (2012). They applied two precipitation correction methods to a historic 20 year record, and evaluated the resulting precipitation data sets through a comprehensive water resources model in Denmark. They found that simulated stream discharge was improved significantly and optimized model parameters were much more physically plausible using the other correction method. However, our results are only preliminary since a more profound research with WSFS could not easily be implemented herein. This analysis supports a comprehensive future research with new calibrations of the modelling system using different precipitation data sets made explicitly comparable. The amount of liquid precipitation correction was considered approximately correct and the amount of solid precipitation correction a bit too large. The results indicated that the coefficients for solid precipitation might be fitted even below the limitation 0.9–1.1.

Conclusions

Aerodynamic, wetting and evaporation correction was carried out for daily precipitation observed in Finland and its cross-boundary catchments in 1961–2011. The correction method was found easy to apply to Finnish conditions. The most time-consuming part was obtaining and combining data from different sources and replacing missing data.

In comparison between corrected and observed precipitation, the proportions and amounts were found to be realistic and in accordance with those in the literature. The mean yearly precipitation sums of all the stations and the whole period were 590.3 mm and 670.6 mm for observed and corrected precipitation, respectively, which is equivalent to a 13.6% increase. The general pattern of spatial variation of total corrected precipitation and its different forms corresponded to the prevailing knowledge and former research.

The distribution of the correction factor varies so that the mode was smaller and its occurrence more frequent for liquid than for solid precipitation in the intensity intervals with the exception of the lowest one (< 1 mm day^{-1}). This was due to the greater aerodynamic correction of the solid form. With low intensities during the summer months, the liquid form had a more frequently higher correction factor because of the greater evaporation correction. The variation of the correction factor was virtually negligible with liquid precipitation greater than 5 mm day^{-1}. The median correction factor on daily basis was 1.21.

In the comparison of different components, the average overall proportions were 8.6, 22.8 and 68.6% for evaporation, wetting and aerodynamic corrections, correspondingly. In the case of solid precipitation, the proportions of the aerodynamic correction were about 89.1% and 77.1% for Period1 (Wild gauges 1961–1981) and Period2 (Tretjakov 1982–1991 and H&H-90 1992–2011), correspondingly. In the case of liquid precipitation, these proportions were 38.8% and 23.3%.

In the analysis of the long-term annual precipitation sums, the observed, corrected total and corrected liquid precipitation were found to be greater and corrected solid precipitation lesser in Period2 than in Period1. For the entire studied period, the linear trend analysis indicated increasing amounts of observed, corrected total and liquid precipitation and decreasing amounts of corrected solid precipitation. In Period1, all the trends were positive but in Period2 the trends were mixed: positive for liquid precipitation and negative for both corrected total and corrected solid precipitation. It cannot be rejected that these trends are real, but they remain obscure for the time being because the vast amount of data used included a lot of heterogeneity.

Although conclusions cannot be drawn on climatic issues, this study provides a large, carefully checked data source to be used for operational hydrological modelling, as originally intended, and also for hydrological and climate research after appropriate data selection for the purpose. According to our literature review, studies on systematic, operational correction of all daily precipitation observations during fifty years are very rare. The correction procedure was developed so that it can be executed automatically when a new observation is received. The procedure utilizes available information in a diverse and effective way using alternative methods or data replacement schemes. We showed that accounting for exposure information of the gauges has a statistically significant decreasing effect on correction amounts. Our method evaluation is not only based on the literature review but also on comparisons with radar and hydrological model based estimates. However, the conclusions drawn are divergent for solid precipitation; the former comparison indicates underestimation and the latter overestimation on the average level when using our procedure. Liquid precipitation correction is instead on a correct level indicated by the hydrological model comparison. Using corrected precipitation as input in hydrological model simulations seems favourable but a more comprehensive study on this topic is recommended.

Acknowledgements: The authors are particularly grateful to Mr. Pauli Rissanen (Finnish Meteorological Institute, retired) for his ideas and guidance in applying the presented procedure and for providing the data, to Dr. Reijo Solantie (Finnish Meteorological Institute, retired) and Dr. Bertel Vehviläinen) for their valuable comments on this study, to Mr. Ari Koistinen (Finnish Environment Institute) for the rewarding discussions on the hydrological model and to Mr. Kalle Sippel and Mr. Juha Markkula (Finnish Environment Institute) for their help in producing the figures.

References

Adam J.C. & Lettenmaier D.P. 2003. Adjustment of global gridded precipitation for systematic bias. *J. Geophys. Res.* 108(D9), 4257, doi:10.1029/2002JD002499.

Allerup P. & Madsen H. 1980. Accuracy of point precipitation measurements. *Nord. Hydrol.* 11: 57–70.

Allerup P., Madsen H. & Vejen F. 1997. A comprehensive model for correcting point precipitation. *Nord. Hydrol.* 28: 1–20.

Allerup P., Madsen H. & Vejen F. 2000. Correction of precipitation based on off-site weather information. *Atmos. Res.* 53: 231–250.

Bell T.L. & Kundu P.K. 2003. Comparing satellite rainfall estimates with rain gauge data: Optimal strategies suggested by a spectral model. *J. Geophys. Res.* 108(D3), 4121, doi:10.1029/2002JD002641.

Benson C.S. 1982. *Reassessment of winter precipitation on Alaska's Arctic slope and measurement on the flux of wind blown snow.* Report UAG R-288, Geophysical Institute, University of Alaska, Fairbanks.

Bogdanova E.F., Ilyin B.M. & Dragomilova I.V. 2002. Application of a comprehensive bias-correction model to precipitation measured at Russian North Pole drifting stations. *J. Hydrometeorol.* 3: 700–713.

Chvíla B., Sevruk B. & Ondrás M. 2005. The wind-induced loss of thunderstorm precipitation measurements. *Atmos. Res.* 77: 29–38.

Collier C.G. 1986a. Accuracy of rainfall estimates by radar, part I: calibration by telemetering raingauges. *J. Hydrol.* 83: 207–223.

Collier C.G. 1986b. Accuracy of rainfall estimates by radar, part II: comparison with raingauge networks. *J. Hydrol.* 83: 225–235.

Dahlström B. 1970a. A general classification of error sources in raingauging and some applications. In: *Nordisk Hydrologisk Konferens, Stockholm 27–29 Aug. 1970*, vol. 2, Nordisk Hydrologisk Förening, Lund, pp. 57–70.

Dahlström B. 1970b. Automatic error checking and correction of rainfall data. In: *Nordisk Hydrologisk Konferens, Stockholm 27–29 Aug. 1970*, vol. 2, Nordisk Hydrologisk Förening, Lund, pp. 79–87.

Dahlström B., Aune B., Førland E., Madsen H., Perälä J. & Solantie R. 1986. *The improvement of point precipitation data on an operational basis. Description of a general method for point precipitation correction with regard to application in practice.* NHP Report no. 17, NHP Working Group on Precipitation, Nordic Hydrologic Programme (NHP), SMHI, Norrköping, Sweden.

Finland's Fifth National Communication under the United Nations Framework Convention on Climate Change 2009. Ministry of the Environment and Statistics Finland, Helsinki, Finland.

Førland E.J. & Hanssen-Bauer I. 2000. Increased precipitation in the Norwegian Arctic: true or false? *Clim. Change* 46: 485–509.

Fuchs T., Rapp J., Rubel F. & Rudolf B. 2001. Correction of synoptic precipitation observations due to systematic measuring errors with special regard to precipitation phases. *Phys. Chem. Earth B* 26: 689–693.

Førland E.J., Allerup P., Dahlström B., Elomaa E., Jónsson T., Madsen H., Perälä J., Rissanen P., Vedin H. & Vejen F. 1996. *Manual for operational correction of Nordic precipitation data. Nordic working group on precipitation.* Report no. 24/96, Norwegian Meteorological Institute, Oslo.

Gjertsen U. & Dahl J.I. 2001. *Development of a gauge adjustment method for correction of radar precipitation estimates.* DNMI Research Report no. 128.

Goodison B.E., Sevruk B. & Klemm S. 1989. WMO solid precipitation measurement intercomparison: objectives, methodology, analysis. In: Delleur J.W. (ed.), *Atmospheric deposition*, IAHS Publication 179, Baltimore, MD, pp. 57–64.

Goodison B.E., Louie P.Y.T. & Yang D. 1998. *WMO solid precipitation measurement intercomparison. Final report. Instruments and observing methods, report no. 67*. WMO/TD No. 872, World Meteorological Organization, Geneva, Switzerland.

Groisman P.Ya., Koknaeva V.V., Belokrylova T.A. & Karl T.R. 1991. Overcoming biases of precipitation measurement: a history of the USSR experience. *Bull. Am. Meteorol. Soc.* 72: 1725–1732.

Helminen V.A. 1987. Temperature conditions. In: Alalammi P. (ed.), *Atlas of Finland. Folio 131, Climate*, National Board of Survey and Geographical Society of Finland, Helsinki, Finland, pp. 2–5.

Helminen V.A., Sarkkula S. & Solantie R. 1987. Atmospheric pressure and winds. In: Alalammi P. (ed.), *Atlas of Finland, Folio 131, Climate*, National Board of Survey and Geographical Society of Finland, Helsinki, Finland, pp. 5–6.

Huovila S., Elomaa E., Leminen K., Tammelin B. & Tuominen A. 1988. *Comparison of snow gauges used in Nordic countries — Contribution of Finland to WMO solid precipitation measurement intercomparison. Part I: System description*. Meteorological publications no. 9, Finnish Meteorological Institute, Helsinki, Finland.

Huttunen I., Huttunen M., Piirainen V., Korppoo M., Lepistö A., Räike A., Tattari S. & Vehviläinen B. 2016. A national scale nutrient loading model for Finnish watersheds — VEMALA. *Environmental Modeling and Assessment* 21: 83–109.

Koistinen J., Michelson D.B., Hohti H. & Peura M. 2004. Operational measurement of precipitation in cold climates. In: Meischner P. (ed.), *Weather radar. Principles and advanced applications*, Springer-Verlag, Berlin, Germany, pp. 110–114.

Korhonen V.V. 1942. Die Verteilung der Niederschläge, besonderes der Schneefälle auf die verschiedenen Windrichtungen in Finnland. *Ann. Acad. Sci. Fenn. Ser. A1 Math.-Phys.* 13: 1–54.

Korhonen V.V. 1944. Ein neues Verfahren bei der Korrektion der Schneemessungen. *Ann. Acad. Sci. Fenn. Ser. A1 Math.-Phys.* 24: 1–14.

Lapin M. & Šamaj F. 1991. III: Methods of correcting for systematic errors in atmospheric precipitation measurements in Czechoslovakia. *Hydrol. Process.* 5: 243–250.

Legates D.R. & Willmott C.J. 1990. Mean seasonal and spatial variability in gauge-corrected, global precipitation. *Int. J. Climatol.* 10: 111–127.

Legates D., Yang D., Quiring S., Freeman K. & Bogart T. 2005. *Bias adjustment to arctic precipitation: a comparison of daily versus monthly bias adjustments. 8th Conference on polar meteorology and oceanography*. American Meteorological Society, Boston MA (USA). Available at https://ams.confex.com/ams/Annual2005/techprogram/paper_86285.htm and on CD-ROM.

Metcalfe J.R., Ishida S. & Goodison B.E. 1994. A corrected precipitation archive for the Northwest Territories. In: Stewart J.C. (ed.), *Mackenzie Basin Impact Study, Interim Report 2, Proc. Sixth Biennial AES/DIAND Meeting on Northern Climate, Yellowknife, North West Territories, April 10–14, 2014*, Environment Canada, pp. 110–117.

Michelson D.B. 2004. Systematic correction of precipitation gauge observations using analyzed meteorological variables. *J. Hydrol.* 290: 161–177.

Milton J.S. & Arnold J.C. 1987. *Probability and statistics in the engineering and computing sciences*. McGraw-Hill, Inc., Singapore.

Nitu R. & Wong K. 2010. *CIMO survey on national summaries of methods and instruments for solid precipitation measurement at automatic weather stations. Instruments and observing methods. Report No. 102*. WMO/TD No. 1544, World Meteorological Organization, Geneva.

Peel M.C., Finlayson B.L. & McMahon T.A. 2007. Updated world map of the Köppen-Geiger climate classification. *Hydrol. Earth Syst. Sci.* 11: 1633–1644.

Pirinen P., Simola H., Aalto J., Kaukoranta J.-P., Karlsson P. & Ruuhela R. 2012. *Climatological statistics of Finland 1981–2010*. Reports 2012:1, Finnish Meteorological Institute, Helsinki, Finland.

Rasmussen R., Baker B., Kochendorfer J., Meyers T., Landolt S., Fischer A.P., Black J., Theriault J., Kucera P., Gochis D., Smith C., Nitu R., Hall M., Cristanelli S. & Gutmann E. 2011. How well are we measuring snow? *Bulletin of the American Meteorological Society*, doi: 10.1175/BAMS-D-11-00052.1.

Saltikoff E., Lopez P., Taskinen A. & Pulkkinen S. 2015. Comparison of quantitative snowfall estimates from weather radar, rain gauges and a numerical weather prediction model. *Boreal Env. Res.* 20: 667–678.

Sarkanen A. 1989. *The method for correcting the wind error of point precipitation measurements. Meteorological publications no. 13*. Finnish Meteorological Institute, Helsinki, Finland. [In Finnish with English summary].

Schlichting H. 1968. *Boundary-layer theory*, 6th ed. McGraw-Hill, New York, USA.

Schwarz K.T., Patzek T.W. & Silin D.B. 2009. Dispersion by wind of CO_2 leaking from underground storage: Comparison of analytical solution with simulation. *Int. J. Greenhouse Gas Control* 3: 422–430.

Sevruk B. 1982. *Method of correction for systematic error in point precipitation measurement for operational use*. WMO No. 589, WMO, Geneva.

Sevruk B. (ed.) 1986a. *Correction of precipitation measurements. ETH/IAHS/WMO Workshop on the Correction of Precipitation Measurements, Zurich 1–3 April 1985*. Geographisches Institut, Eidgenössische Technische Hochschule, Zürich, Switzerland.

Sevruk B. 1986b. Correction of precipitation measurements. Summary report. In: Sevruk B. (ed.), *Correction of Precipitation Measurements ETH/IAHS/WMO Workshop on the Correction of Precipitation Measurements, Zurich 1–3 April 1985*, Geographisches Institut, Eidgenössische Technische Hochschule, Zürich, Switzerland, pp. 13–23.

Sevruk B. (ed.) 1989a. *Precipitation Measurement. WMO/IAHS/ETH Workshop on Precipitation Measurement. St. Moritz, 3–7 December 1989*. Swiss Federal Institute of Technology, Zurich, Switzerland.

Sevruk B. 1989b. Reliability of precipitation measurements. In: Sevruk B. (ed.), *Precipitation Measurement. WMO/IAHS/ETH Workshop on Precipitation Measurement. St. Moritz, 3–7 December 1989*, Swiss Federal Institute of Technology, Zurich, Switzerland, pp. 13–19.

Sevruk B., Ondras M. & Chvila B. 2009. The WMO precipitation measurement intercomparisons. *Atmos. Res.* 92: 376–380.

Solantie R. 1986. A quantitative model for point precipitation correction by use of data from standard meteorological stations. In: Sevruk B. (ed.), *Correction of Precipitation Measurements ETH/IAHS/WMO Workshop on the Correction of Precipitation Measurements, Zurich 1–3 April 1985*, Geographisches Institut, Eidgenössische Technische Hochschule, Zürich, Switzerland, pp. 197–202.

Solantie R. 1987. Precipitation and snow cover. In: Alalammi P. (ed.), *Atlas of Finland. Folio 131, Climate*, National Board of Survey and Geographical Society of Finland, Helsinki, Finland, pp. 7–8.

Solantie R. & Pirinen P. 2006. *Consideration of the orographical effect in the areal analysis of October–March precipitation*. Reports no. 2006:8, Finnish Meteorological Institute, Helsinki, Finland [In Finnish with English summary and figure captions].

Solantie R., Drebs A., Hellsten E. & Saurio P. 1996. *Timing and duration of snow cover in Finland 1961–1993*. Meteorological publications no. 34, Finnish Meteorological Institute, Helsinki, Finland [In Finnish with English summary].

Stisen S., Højberg A.L., Troldborg L., Refsgaard J.C., Christensen B.S.B., Olsen M. & Henriksen H.J. 2012. On the importance of appropriate precipitation gauge catch correction for hydrological modelling at mid to high latitudes. *Hydrol. Earth Syst. Sci.* 16: 4157–4176.

Sugiura K., Ohata T. & Yang D. 2006. Catch characteristics of precipitation gauges in high-latitude regions with high winds. *J. Hydrometeorol.* 7: 984–994.

Tammelin B. 1984. *On the wind error of the Finnish raingauge*. Meteorological publications no. 37, Finnish Meteorological Institute, Helsinki, Finland. [In Finnish with English summary].

Vehviläinen B., Huttunen M. & Huttunen I. 2005. Hydrological forecasting and real time monitoring in Finland: The watershed simulation and forecasting system (WSFS). In: Balabanis P., Lumbroso D. & Samuels P. (eds.), *Innovation, Advances and Implementation of Flood Forecasting Technology, Conference Papers, Tromsø, Norway, 17–19 October 2005*, available at http://www.actif-ec.net/conference2005/proceedings/PDF%20docs/Session_03_Pre-operational_flood_forecasting/Vehvilainen_Bertel.pdf.

Wagner A. 2009. *Literature study on the correction of precipitation measurements*. FutMon C1-Met-29(BY), Bayerische Landesanstalt für Wald und Forstwirtschaft.

Wolff M., Isaksen K., Brækkan R., Alfnes E., Petersen-Øverleir A. & Ruud E. 2013. Measurements of wind-induced loss of solid precipitation: description of a Norwegian field study. *Hydrol. Res.* 44: 35–41.

Yang D. 1999. An improved precipitation climatology for the Arctic Ocean. *Geophys. Res. Lett.* 26: 1625–1628.

Yang D. & Ohata T. 2001. A bias-corrected Siberian regional precipitation climatology. *J. Hydrometeorol.* 2: 122–139.

Yang D., Goodison B.E. & Metcalfe J.R. 1998. Accuracy of NWS 8″ standard nonrecording precipitation gauge: Results and application of WMO intercomparison. *J. Atmos. Ocean. Tech.* 15: 54–68.

Yang D., Ishida S., Goodison B.E. & Gunther T. 1999. Bias correction of daily precipitation measurements for Greenland. *J. Geophys. Res.* 104(D6): 6171–6181.

Yang D., Goodison B.E., Metcalfe J.R., Golubev V.S., Elomaa E., Günther Th., Bates R., Pangburn T., Hanson C.L., Emerson D., Copaciu V. & Milkovic J. 1995. Accuracy of Tretjakov precipitation gauge: result of WMO intercomparison. *Hydrol. Process.* 9: 877–895.

Ye B., Yang D., Ding Y., Han T. & Koike T. 2004. A bias-corrected precipitation climatology for China. *J. Hydrometeorol.* 5: 1147–1160.

Zhang Y., Ohata T., Yang D. & Davaa G. 2004. Bias correction of daily precipitation measurements for Mongolia. *Hydrol. Process.* 18: 2991–3005.